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"A Correlative Investigation of the Propagation of ULF Wave Power Through  
the Dayside Magnetosphere"

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(NASA-CR-187784) A CORRELATIVE  
INVESTIGATION OF THE PROPAGATION OF ULF WAVE  
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## I. Overview

In response to a 1988 NASA Research Announcement we submitted to NASA a research and analysis proposal requesting funding for two years to support a multisatellite study of the propagation of ULF wave power through the dayside magnetosphere using magnetic field data from GOES 5, GOES 6, and AMPTE CCE. Project funding began in January 1989 as NASA grant NAGW-1567, and was extended for a second year, through December 1990. This project has supported studies of three different ULF wave phenomena (azimuthally polarized Pc 3 pulsations, radially polarized Pc 4 pulsations, and solitary Pc 5 pulsations related to solar wind pressure pulses). We now request continuation of this study for one more year. Included in the work to be proposed under this continuation will be one new task and extension of work on two projects currently underway.

During the period covered by this report, July 1, 1990 through December 31, 1990, we continued work on three studies, presented further developments of these studies at national conferences, and began work on a fourth study. Dr. Engebretson presented some of the results of this project as part of an invited talk at the 1990 Cambridge Workshop on Theoretical Geoplasma Physics [Engebretson et al., 1990d], and also presented one of these studies at the 1990 Western Pacific Geophysics Meeting in Japan [Engebretson et al., 1990e]. Drafts of three papers have been prepared, but none has yet been submitted for journal publication.

## II. Scientific Background

The earliest studies of geomagnetic pulsations were based on data from ground observatories or from single satellites, usually in geosynchronous orbit. These satellites remained at fixed radius and geomagnetic latitude, but their passage through all local times and seasons and their continuous data records for long intervals of time made it possible to identify several consistent features in pulsation data. In particular, Cummings et al. [1969] verified that many of the pulsations observed at synchronous orbit were standing Alfvén waves in the magnetosphere. More recently, Takahashi and McPherron [1982] noted the frequent occurrence of harmonically related azimuthally polarized pulsations in the dayside hemisphere, and Takahashi et al. [1981, 1984a,b] were able to use a large data base to investigate factors controlling the occurrence and properties of these waves.

The launch of the AMPTE CCE satellite has provided an opportunity to extend the knowledge gained from studies at synchronous orbits to radial distances of nearly 9 earth radii. Because of its highly elliptical orbit, it traverses the near-equatorial magnetosphere in a trajectory nearly perpendicular to that of geosynchronous satellites. Like many satellites at geosynchronous orbit, the AMPTE CCE satellite also records data continuously, providing a nearly unbroken time record as it traverses large portions of the magnetosphere. Studies of AMPTE CCE magnetic fields data have revealed several new features of the distribution of mid- and long- period ULF pulsations in the outer magnetosphere, including local field line resonant properties of Pc 3, Pc 4, and Pc 5 pulsations and a clear dependence of Pc 3-4 pulsation occurrence on upstream IMF orientation [Engebretson et al., 1987, 1988]. In addition, a statistical study of ULF pulsations by Anderson et al. [1990], covering all local times and all

field components using data from the AMPTE CCE satellite, provided the first two-dimensional coverage of pulsation types and occurrence rates in the equatorial outer magnetosphere. On a statistical basis, Anderson et al. [1990] found distinct spatial occurrence patterns for Pc 3-4 pulsations (azimuthally polarized), Pc 4 pulsations (radially polarized), and Pc 5 pulsations (predominantly transversely polarized). This massive study added further support to suggestions of many others that there are multiple sources for long-period ULF pulsations.

Single-satellite studies, whether from AMPTE CCE or from geosynchronous satellites, however, suffer from being only single-point measurements in a huge volume of magnetospheric plasma. It is for this reason that we proposed a study correlating data from AMPTE CCE and two geosynchronous satellites, GOES 5 and 6. The availability of coordinated data at different local times and (usually) L shells should allow further progress in our understanding of these characteristics. Although the statistical study of Anderson et al. [1990] covered all local times and L shells, continued study of a multisatellite data set is needed to overcome some of the unavoidable limitations in simultaneity of a single-satellite study. In particular, we have found that a multisatellite study provides considerably more information on the spatial structure and extent of such pulsations. The new task proposed here is to also include data from a fourth satellite, AMPTE IRM, which also travels in a highly elliptical equatorial orbit. As will be detailed below, the plasma wave receivers on AMPTE IRM will allow us to begin to study in situ the effects of ULF waves on ELF-VLF waves, and hence on electron precipitation phenomena as these are related to upstream variations.

### III. Scientific Objectives

We list below three questions which this project will address:

- 1) How do magnetospheric Pc 3-4 pulsations, which appear to originate in the solar wind, enter the magnetosphere, and how is this wave energy transported throughout the magnetosphere once it enters?

In our initial proposal for support of this multisatellite study in 1988 we suggested that this effort could provide additional information on how these pulsations enter the magnetosphere; how they are transported throughout the dayside magnetosphere; and whether there are any similarities between the entry/transport of these pulsations and of longer period Pc 5 pulsations. Our recent work, reported by Ho et al. [1990] at the Spring AGU Meeting in Baltimore and by Engebretson et al. [1990e] at the Western Pacific Geophysics Meeting in Japan, indicates surprising localization of Pc 3-4 wave packets, suggesting that the usual assumptions of equatorial wave entry models may be incorrect.

The earliest wave entry mechanism, suggested by Verzariu [1973] and Wolfe and Kaufmann [1975], was transmission of compressional wave power directly across tangential discontinuities at the subsolar magnetopause, after which it can propagate in the fast mode across field lines. This model, along with mode coupling between compressional and transverse waves, is often assumed to be the means by which transverse Pc 3-4 harmonics are excited. Theoretical work by Kwok and Lee [1984] suggested considerably greater efficiency for transmission through rotational discontinuities, which for a nearly radial IMF field

direction might be more dominant at high (and possibly cusp) latitudes. Our recent studies of Pc 3-4 pulsations at South Pole Station using a variety of instruments, including search coil magnetometers, riometer, photometer, and VLF receivers [Engebretson et al., 1990a,b] showed pulsation signatures in all but the riometer, with center frequency equal to that expected for upstream waves in the ion foreshock region upstream of the earth's bow shock,

$$f \text{ ( Hz ) } = 0.006 B_{\text{lmf}} \text{ ( nT ) }.$$

Although observation of the peak in magnetic field spectra at the predicted frequency was anticipated, the presence of a similar peak in the photometer (sensitive to auroral light at 427.8 nm wavelength) was unexpected. This observation suggests a modulation of electrons with magnetosheath- or cusp-like energies at the frequencies determined by upstream waves, and indicates a possible role for such particles in transmitting ULF signals to the high latitude ionosphere. Both our observations at AMPTE CCE and AMPTE IRM [Engebretson et al., 1987] and at South Pole [Engebretson et al., 1986a; 1989a,b; 1990a,b] appear to support models of high latitude entry, although several of these studies indicate that both mechanisms are probably operative. In the last of these papers we presented a new model for such high latitude entry, by means of an "ionospheric transistor."

Because the source of all Pc 3-4 waves has previously been assumed to be localized near the subsolar point, comparisons of the pulsations have focused on azimuthal propagation effects and/or azimuthal wave numbers for these azimuthally polarized waves. The few reported studies have found very low wave numbers, corresponding to very high azimuthal phase velocity, however [cf. Takahashi et al., 1984b], which appeared inconsistent with this wave entry mechanism.

At the beginning of this study we attempted to find pulsations at two or more locations with identical frequency structure but with a location-dependent phase offset. We found that it was much more difficult than anticipated to identify suitable Pc 3-4 pulsation events for spatial/temporal comparison between the GOES 5 and 6 satellites and AMPTE CCE: thus far we have found no azimuthally polarized wave events during which identical frequency and wave packet structure occurred at even two of these three satellites, even when the intersatellite separation was only several tenths of an earth radius. Because of published reports of earlier good conjunctions, however (summarized by Takahashi et al. [1984b]), we assumed that our data were somehow unusual in not containing "good" conjunction events. As our data accumulated, however, we began to realize that, because of the characteristics of the waves themselves, "good" conjunctions were merely accidental, and might have no physical meaning.

We have since learned that earlier studies also experienced difficulties [K. Takahashi, personal communication, 1990]. Takahashi et al. [1984b], who used geosynchronous satellites spaced 20 degrees in longitude, found only one interval with high coherency between them in a total of ten days of data examined. They attributed the generally poor intersatellite coherency to the azimuthal gradient of cold plasma density, so that even two geostationary satellites usually find themselves on different L shells. Although this effect will certainly influence wave behavior in the outer magnetosphere, our data suggest an additional and unexpected possibility: that the wave packets are simply localized in longitude.

As has been found in other recent studies, we found agreement on the order of tens of minutes between upstream satellite observations of predominantly radial IMF orientation and the presence of azimuthally polarized Pc 3-4 pulsation activity. Coherent radial and/or compressional perturbations of Pc 4 or longer periods were often observed over wide intersatellite distances, but only very rarely did Pc 3-4 harmonic activity exhibit any coherence. There are times when radial and compressional polarized perturbations (usually of much longer period) appear to match closely between at least 2 of the 3 satellites, when all are on the dayside, separated by 1 and 2.5 hours of magnetic local time. During some of these same times the Pc 3-4 "packets" of activity do NOT appear at the same times. Wave packets, of from 5 to 20 minutes duration, can be present at one site and essentially absent at another (to the limit of visual resolution and the graininess of the GOES data). They can appear at one satellite or two at one time, and then appear later at another satellite or two. Figure 1 (page 9) shows an example of such observations from the two GOES satellites. Further analysis indicated that compressional power fell off with distance from the subsolar point, but that azimuthally polarized power could be largest at any local time.

The above characteristics appear to cast significant doubt on the conventional pathway for wave entry described above. Although our observations of compressional mode wave power do indeed support models of equatorial, subsolar wave entry, there is little or no observational support in our data for conversion of compressional mode wave power to azimuthally polarized transverse mode wave power. These observations are also difficult to interpret using the global cavity modes model: although radial and compressional pulsations correlate well and appear coherent over distances of several RE, the azimuthally polarized Pc 3-4 harmonics can be very localized.

Alternative models for the entry of upstream waves [Kwok and Lee, 1984; Engebretson et al., 1990b] have suggested possible entry of wave signals at cusp/cleft latitudes, by means of processes that may occur at widely separated locations on the dayside magnetopause. Entry by these mechanisms would also alleviate the azimuthal phase velocity inconsistency raised by the earlier observations.

Our results thus provide unexpected support for high latitude entry models. We need now to confirm our earlier observations, and do a more careful job of showing that the observations are not compatible with a subsolar source of compressional mode waves, followed by mode coupling. This will entail taking into account the magnetic latitude of the three (or more) satellites considered, and performing some quantitative modeling of the expected propagation of compressional mode waves.

2) What is the ULF response of the outer dayside magnetosphere to solar wind pressure pulses?

Multisatellite studies provide the best means of testing recent ideas of global cavity modes, or global resonances, as the source of excitation is often a clearly defined impulsive compression of the dayside magnetosphere. We have identified one such impulsively excited event using data from AMPTE IRM, AMPTE CCE, GOES 5 and 6, DE 1, the DMSP satellites, and a wide range of ground stations and arrays [Engebretson et al., 1989c], and have begun to identify others using the combined AMPTE and GOES data set.

Because of the recent interest in finding examples of global compressional resonances, we have looked for such compressional polarized waves in the satellite data for this event; we have found no evidence so far for any significant periodic variations in the main field. Further details on our work is given below.

3) How do Pc 3-4 pulsations modulate ELF-VLF emissions in the dayside magnetosphere?

Sudden magnetospheric compressions (SI and SC events) have long been known to generate increased levels of ELF-VLF emissions [Gail et al., 1990]. More recently, a certain class of such emissions known as quasiperiodic (QP) emissions has been associated with Pc 3-4 pulsations [Lanzerotti et al., 1986; Morrison, 1990].

During the past two years we have studied the relation between ULF variations in magnetic fields and ELF-VLF waves using data from AMPTE CCE and from Antarctic ground records. We have found that ELF-VLF signals between 500 Hz and ~2000 Hz observed by the Stanford VLF receivers at South Pole Station often showed modulations at the same Pc 3-4 frequencies (10 to ~60 mHz) as were evident in the magnetic field [Engebretson et al., 1990a]. Magnetic pulsations and ELF-VLF modulations at South Pole, and those observed upstream of the bow shock by Russell et al. [1987], were observed to have bandwidths of approximately 20-30 mHz, while individual transverse resonant Pc 3 harmonics observed in the dayside outer magnetosphere were much narrower, with typical bandwidths of order 2-5 mHz.

A followup study using additional ground data, presented at the Spring 1990 meeting of the American Geophysical Union [Engebretson et al., 1990c] indicated that pulsations in both the magnetic field and in VLF emissions often occurred simultaneously (to within minutes) over large distances at high to very high latitudes. The phenomenon is thus a global one, and gives evidence of being an important means of transfer of energy from a presumed upstream (solar wind) source through the magnetosphere and into the ionosphere.

We have been unsuccessful so far in positively identifying quasi-periodic ELF-VLF modulations in the AMPTE CCE electric field data [R. J. Strangeway, private communication, 1990], both because the AMPTE CCE plasma wave experiment has very limited sensitivity (only a short boom is available) and because it provides signals in only five narrowband VLF channels. The plasma wave instrument on AMPTE IRM, however, has sweep frequency receivers, and has been used to record signal levels from the ELF up to well beyond the VLF frequency range. Fortunately, during fall 1984 AMPTE IRM was in an orbit with apogee at essentially the same local time as AMPTE CCE. The availability of magnetic field data from both CCE and IRM, along with plasma wave data from IRM, provides a reasonable basis for testing in situ for the correlation of ULF compressional pulsations with VLF modulations predicted by theory [Coroniti and Kennel, 1970].

Study of the detailed frequency structure of the ELF-VLF modulations in space will help us determine whether the band-limited frequencies of ELF-VLF modulations seen on the ground are due to a superposition of more narrowband transverse modulations in space, perhaps corresponding to local field line resonances, or if the same, moderately broad and featureless frequency structure occurs over a range of L shells in the outer magnetosphere, with center frequency determined solely by the frequencies of upstream waves.

GEOS observations presented by Tixier and Cornilleau-Wehrlin [1986] showed that VLF and ULF signals had the same spectral characteristics, but in their study both the ULF and VLF signals exhibited narrower, multiple frequencies in the Pc 3 band, at the frequencies of local harmonic resonances. We believe it is important to test the observations of Tixier and Cornilleau-Wehrlin [1986]: if their observations are correct, i.e., if locally observed ELF-VLF emissions are truly modulated at narrow-banded harmonically related ULF frequencies, then a new wave-particle interaction mechanism may be needed. If the GEOS results are incorrect, that should also be pointed out to the community.

#### IV. Other Accomplishments to date

As a result of the first two years' effort on this project, we have on hand at Augsburg both digital data and color spectrograms for magnetic field data from AMPTE CCE, GOES 5, and GOES 6 for the intervals September — December 1984 and January — June 1986. We have identified in this data set a large number of radially and azimuthally polarized ULF wave events observed simultaneously at two or three satellites, and have used these sets of events to characterize the spatial extent and localization of both classes of pulsations [Murr et al., 1989; Ho et al., 1990]. A progress report on the Ho et al. [1990] study has been presented as part of objective 1) above. We also presented a paper at the Fall 1989 AGU meeting describing the magnetospheric response to a sudden impulse (SI) event on October 9, 1984 (84283) [Engebretson et al., 1989c]. This event, first identified in satellite data from AMPTE IRM in the magnetosheath, resulted in clear magnetic perturbations at several locations in space and on the ground.

During this SI event the AMPTE IRM satellite was situated in the subsolar magnetosheath, and the AMPTE CCE satellite was located in the subsolar magnetosphere, both at near-equatorial latitudes. For a 2-3 minute period the bow shock was compressed inward past the location of AMPTE IRM, and a large compression and distortion of the magnetospheric field was observed at AMPTE CCE. Particle experiments on AMPTE CCE detected a simultaneous directional dropout of ion flux, indicating a near encounter with the magnetopause, and a strong spike-like increase in low-energy electrons. This increase also appeared to temporarily fill the loss cone. Damped azimuthal pulsations, probably fundamental resonances, occurred at GOES 5 and 6, located near 0800 and 0600 MLT, respectively, but no magnetic pulsation activity was evident at AMPTE CCE. The absence of a magnetic pulsation signature at AMPTE CCE is consistent with its near-equatorial location, however. The MEPA ion detectors and HPCE electron detectors on AMPTE CCE noted the presence of a damped oscillation, again probably corresponding to a fundamental resonance, in the particle fluxes at AMPTE CCE.

This event, and others like it, can be used both to provide a general characterization of the magnetospheric response to SI events, and to provide a test of recent theories describing propagation of wave energy from the magnetopause via global compressional modes. As a followup to our initial study, we have found that this SI caused a large-amplitude Pc 5 impulsive perturbation at South Pole, Antarctica, and at approximately conjugate sites in Greenland. We are pursuing the study of this event using data from these sites as well as from the EISCAT magnetometer cross.

In addition to the potential interest in global modes and spatial scale of the compressional impulse, the AMPTE CCE particle data may be helpful in testing and/or clarifying recent models of ionospheric signatures of SI and SC events by Southwood and Kivelson [1990] and Kivelson and Southwood [1990]. In particular, the observation of large fluxes of electrons in the loss cone at near-equatorial locations near the nose of the magnetosphere may be significant in understanding the origin of the ionospheric "vortex events" observed at cusp/cleft latitudes, which have been claimed by some to be the consequence of flux transfer event (FTE) production at the magnetopause. Work is continuing on this event, focusing mainly on finding similar events and on working with Lockheed personnel to understand the characteristics of the plasma data observed by the AMPTE CCE Hot Plasma Composition Experiment (HPCE).

The study of Murr et al. [1989], also presented at the Fall 1989 AGU meeting, focused on radially polarized ULF events. Neither the nature of these pulsations nor their energy source is well understood. We were able to find sixteen multi-satellite events in our data set: in eight cases pulsations were observed simultaneously but at different local times by GOES 5 and GOES 6, and in eight other cases pulsations were observed also by AMPTE CCE. Although it has been known for some time that some radially polarized pulsation events are extended in longitude/local time, the combination of GOES observations in a circular (synchronous) orbit and AMPTE CCE observations in an elliptical but still near-equatorial orbit have provided the first information on the radial extent of these events. We have found in each of the eight three-satellite cases studied that the radial extent was narrow. The width in L value varied from 0.3 to 3.0, with a mean of 0.9. The longitudinal extent was much more variable, ranging from 6 hours magnetic local time difference down to the minimum 1.5 hours MLT resolution required for a "simultaneous" event.

The frequently sharp spatial boundaries observed for these events in both the radial and longitudinal directions (see Figure 2 on page 10 for an example) suggest that some property of the background plasma may be responsible, either as an energy source or as a medium with a favorable growth rate. Our further study of these events has focused on providing a detailed characterization of selected events and searching for such distinctive plasma characteristics. We have contacted other satellite investigators, both on AMPTE CCE and on various synchronous orbit satellites, in order to obtain relevant particle data.

David Murr, the undergraduate student supported by this project, was chiefly responsible for preparation of the study of radially polarized pulsations described above. He competed in the student paper competition at the AGU meeting, and was awarded an Honorable Mention in what is usually a competition only among GRADUATE students. This award has given David, who is now a junior, significant encouragement toward a career in space physics, and reinforces his already strong interest in pursuing studies leading to a Ph. D. degree.

#### V. Plans for Extended Research

Because all of the data needed for this comparative study are now processed in standard form, no time or effort needs to be invested in preparatory data presentations. Such effort may still be necessary for AMPTE IRM magnetic field data and plasma wave data from both AMPTE IRM and DE 1, however. Specific tasks are outlined below:



a. We will continue to compare local time, L shell, and/or universal time differences and effects on Pc 3-4 pulsations due to wave propagation, with the goal of understanding the mechanism or mechanisms of energy transport into and within the magnetosphere.

b. We will undertake a joint study of data from the three magnetospheric satellites, from IMP 8 and/or AMPTE IRM upstream, and if possible from high latitude ground stations in Antarctica, focusing on local time and radial differences in the response of magnetospheric regions to the occurrence of solar wind pressure pulses.

c. We will begin a comparison of relevant data from the AMPTE CCE, AMPTE IRM, and DE 1 satellites, and ground data from South Pole Station, McMurdo, and/or Sondreström fjord, in an attempt to gain further understanding of the mechanism of ULF modulation of ELF-VLF emissions during times when both appear to be controlled by upstream conditions.

Wolfgang Baumjohann of the Max Planck Institute for Extraterrestrial Physics and Hermann Luehr of the Technical University of Braunschweig, both in Germany, have provided us with AMPTE IRM magnetic field and plasma data in digital form for several events studied under this project as well as for other correlative AMPTE CCE / IRM studies. We propose here to continue to access modest amounts of such data, and to work with Roger Anderson of the University of Iowa to compare plasma wave data from AMPTE IRM and Dynamics Explorer 1 with magnetic field data from the two satellites.

## VI. Figures

Figure 1: Simultaneous magnetic field data at 3 second resolution from GOES 5 (left) and GOES 6 (right) from 1500 to 1600 UT September 12, 1984. From top to bottom the panels show the BV (radial), BD (azimuthal), and BH (northward) components.

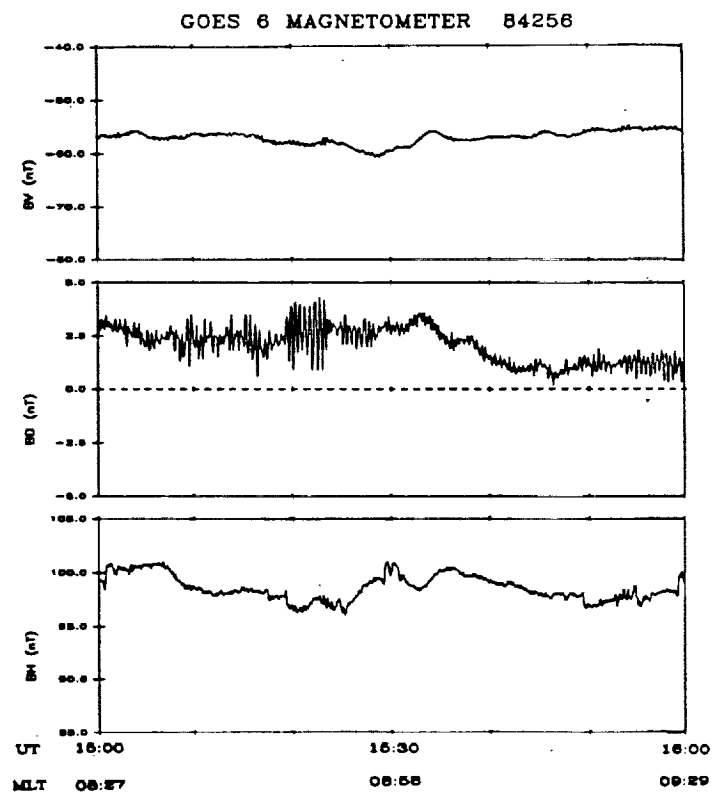
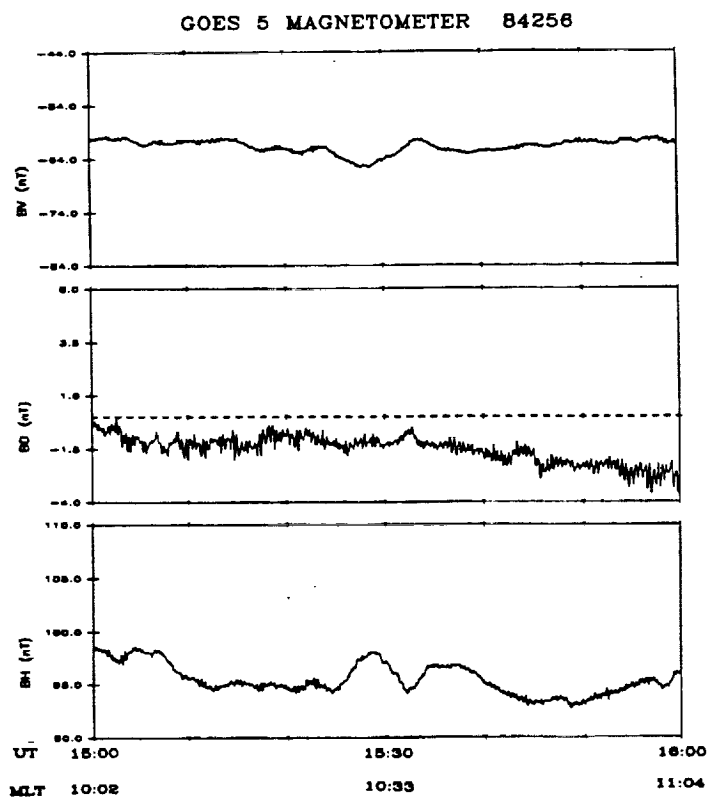
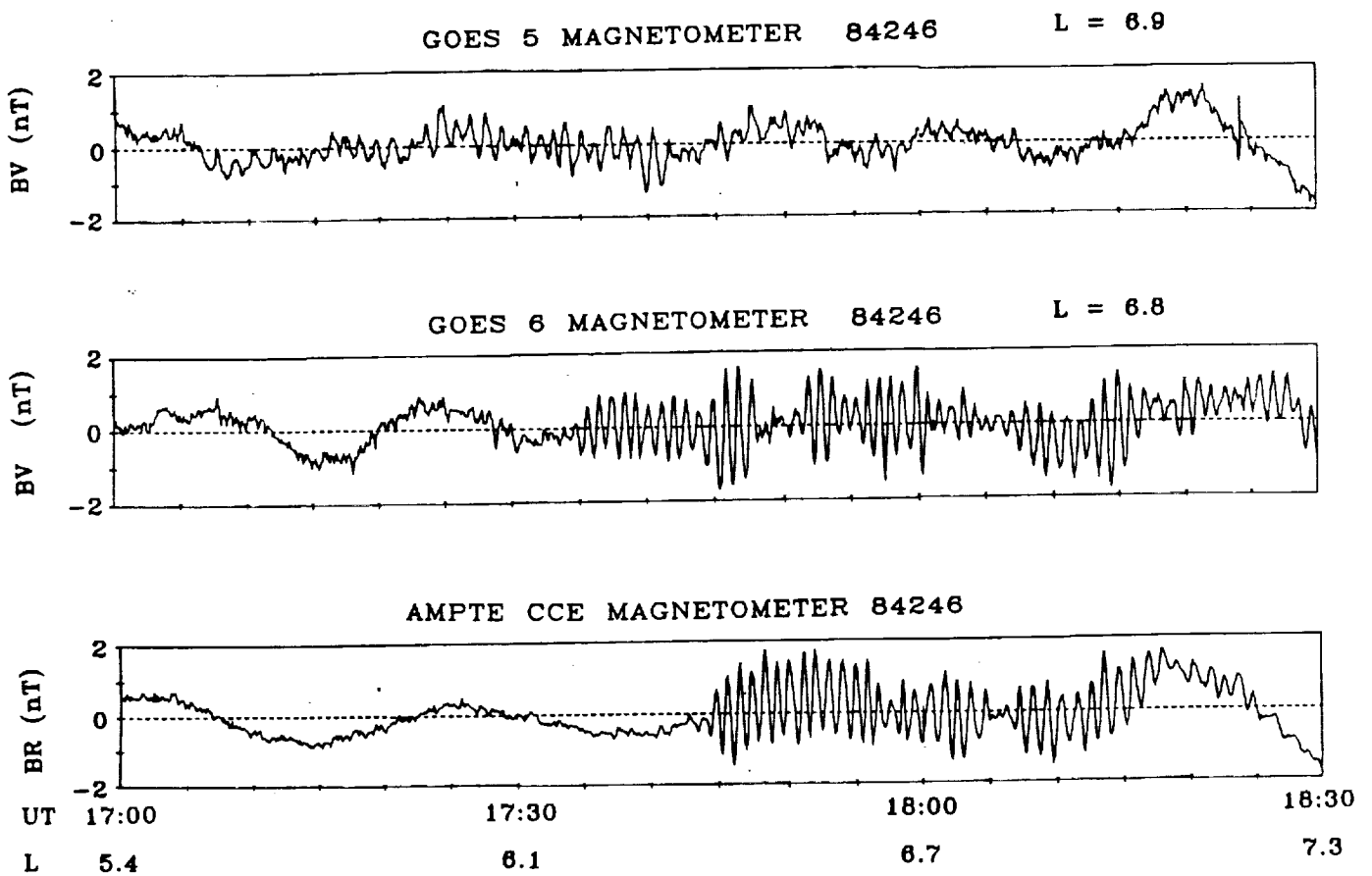


Figure 2: Waveform plot of the radial component of magnetic field data from AMPTE CCE, GOES 5, and GOES 6 from 1700 to 1830 UT September 2, 1984 (84246), during a radially polarized Pc 4 pulsation event. The upper two panels are cuts in local time at constant L (from satellites in geostationary orbit), while the bottom panel is a cut primarily in L at a local time midway between that of the GOES satellites.



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# BUDGET

January 1991 - December 1991

## SALARIES AND WAGES

1. Principal Investigator  
Mark Engebretson, Professor of Physics  
1/2 month during summer 1991  
1/7 time during the 1991 academic year  
(see budget detail)

\$ 2120.00

3. Undergraduate Research Assistant  
500 hours @ \$6.75/hour

\$ 5451.43

## FRINGE BENEFITS

1. Faculty benefits @ 30%
2. Student FICA @ 7.65%

\$ 3375.00

\$ 2271.43  
\$ 258.19

## SALARY SUBTOTAL

\$ 13476.05

## TRAVEL

Two trips to an AGU national meeting @ \$900

\$ 1800.00

## SUPPLIES

1. Computer Maintenance
2. Computer Materials and Supplies: paper, graphics supplies, magnetic media
3. Publication Costs (JGR or GRL, including charges for color figures)

\$ 3000.00

\$ 1000.00

\$ 1000.00

\$ 20276.05

\$ 4716.62

## TOTAL DIRECT COSTS

INDIRECT COSTS @ 35% of total salary costs

## TOTAL BUDGET REQUEST

\$ 24992.67